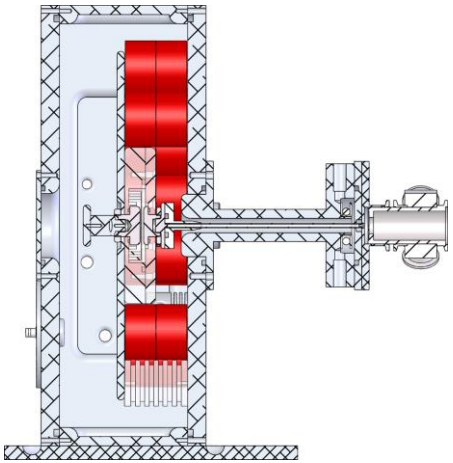
CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF NUCLEAR SCIENCES AND PHYSICAL ENGINEERING

Water window radiation from 40 kA Z-pinching capillary discharge plasma

M. Nevrkla, A. Jančárek

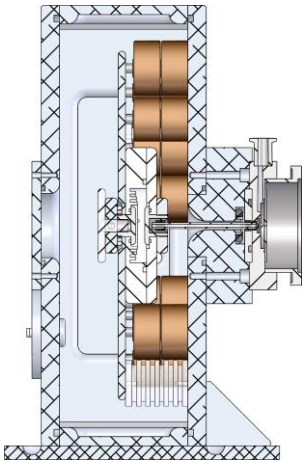
2014 International Workshop on EUV and Soft X-Ray Sources, Dublin, Ireland, November 3-6 ,2014

DISCHARGE DRIVERS DEVELOPED AT FNSPE CTU since 2009



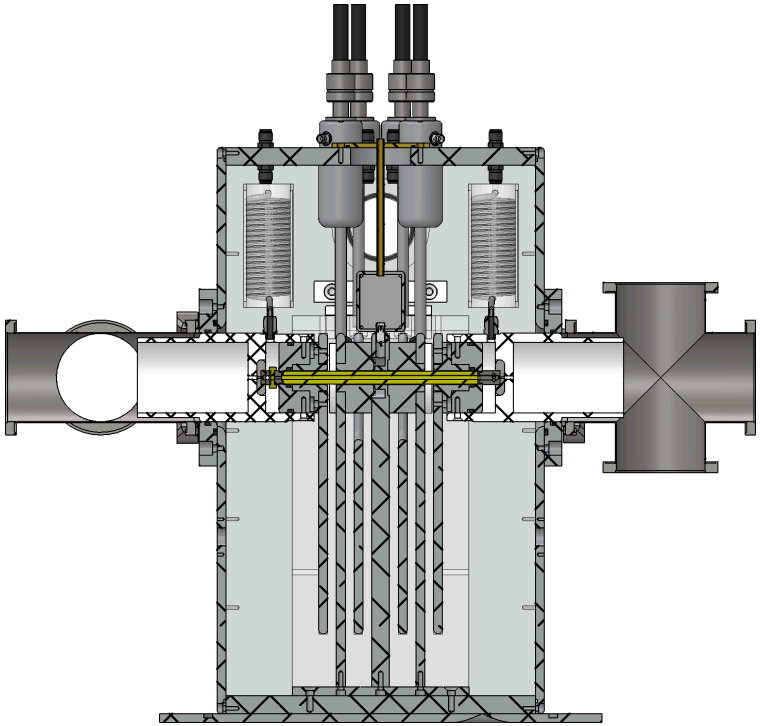
2009

- **lasing at 46.9 nm**
- inspired by design of J.J. Rocca's group
- ~10^{12} ph/Sr at 2.88 nm
- 5 Hz



2011

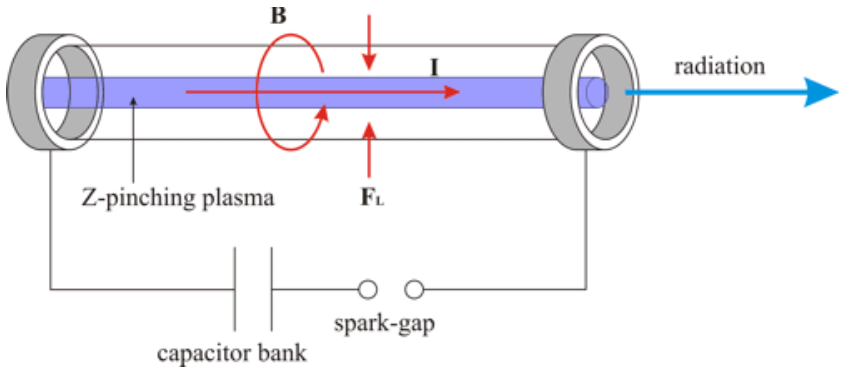
- **modification for 2.88 nm**
- ~10^{13} ph/Sr at 2.88 nm
- multiple Z-pinch
- 5 Hz



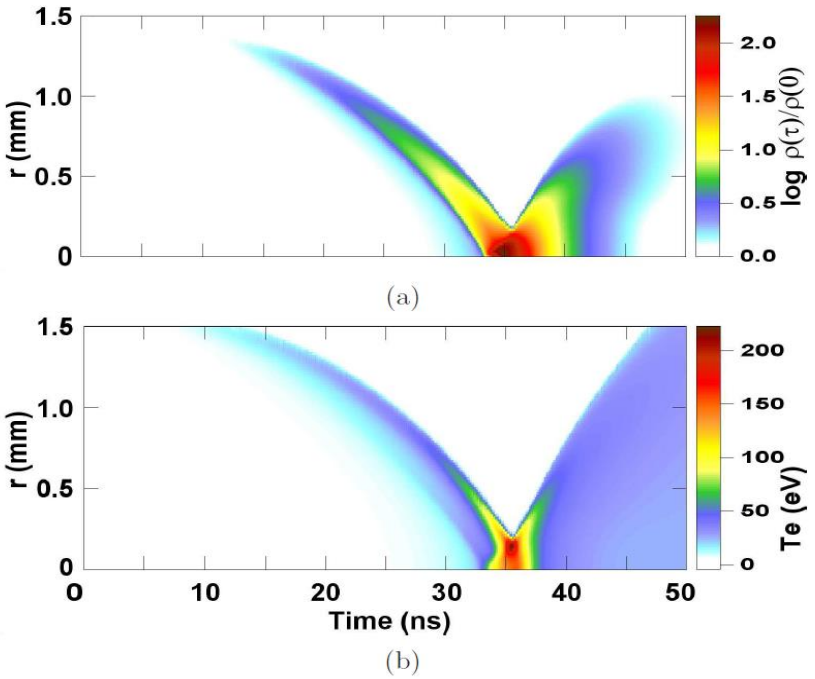
2013

- **driver for 13.4 nm laser**
- full-rate current not reached yet
- ~10^{14} ph/Sr at 2.88 nm
- 1 Hz

Z-PINCHING CAPILLARY DISCHARGE

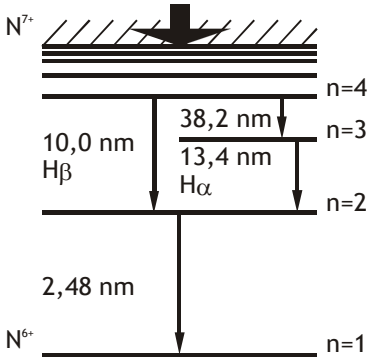


- Plasma heating by **shock thermalization**
- Plasma cooling by fast **adiabatic expansion**
- Long (~ 10s cm) **thin** (~ 100s um) **plasma column**
- **Stabilization by pre-ionization** discharge
- **ASE** - No mirrors -> high gain needed *G* ~ 1

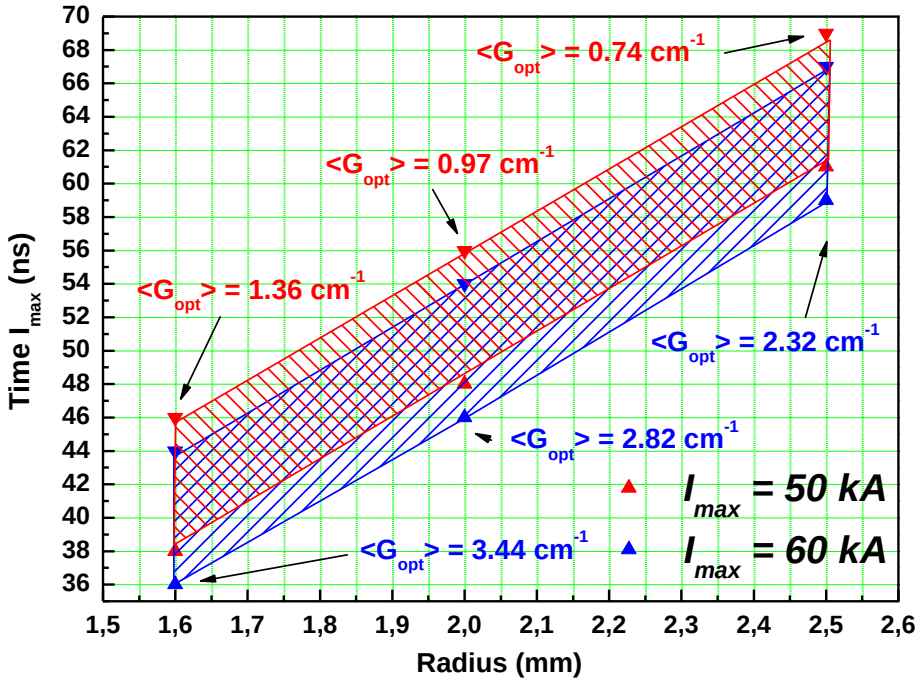


P. Vrba, M. Vrbová, N. A. Bobrova, and P. V. Sasorov, "Modelling of a nitrogen x-ray laser pumped by capillary discharge," *Cent. Eur. J. Phys.*, vol. 3, no. 4, pp. 564–580, 2005

3B-RECOMBINATION PUMPING SCHEME OF 13.4 NM LASER

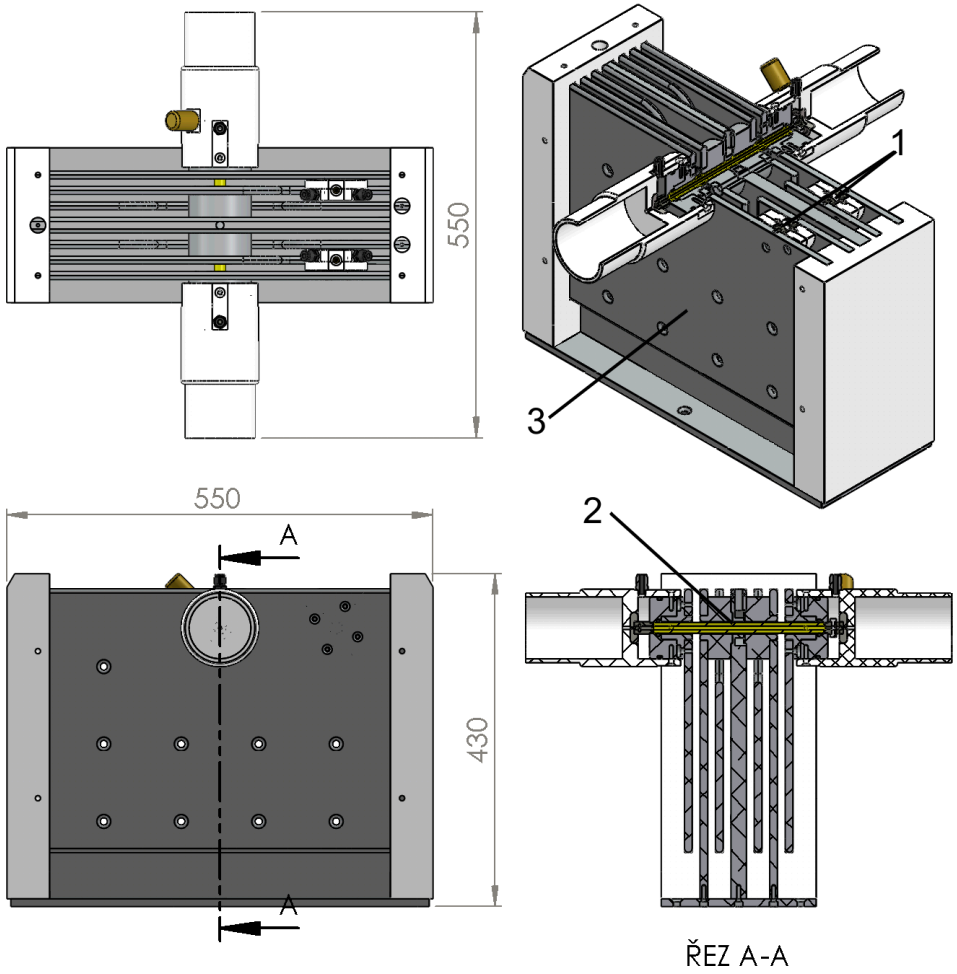


- **Electron temperature T_e**
  - >50% abundance of fully striped ions -> initial $T_e > 140$ eV
  - high 3b-recombination rate -> drop of $T_e < 60$ eV
- **Electron density N_e**
  - $N_e > 10^{19}$ cm^{-3} to ensure high 3b-recombination rate
  - limited to $N_e \approx (5 \div 10) \times 10^{19}$ cm^{-3} (to reduce collision excitation into lower laser level 2)
- **Cooling time**
  - faster then 3-b recombination rate $\beta^{-1}(T_e = 60$ eV, $N_e = 4 \cdot 10^{19}$ cm$^{-3}) \approx 5$ ns



Optimized discharge condition for ASE at 13,4 nm – Jakub Hübner

DISCHARGE DRIVER



CAD model of discharge driver. 1 – spark-gaps, 2 – capillary, 3 – water capacitor

-> **Slab water capacitor design with pulse compression**:

+ **table top** size of the driver

+ well **shielded capillary**

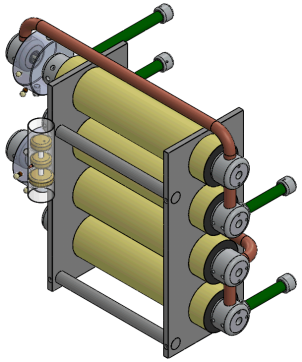
22.4 cm long capillary (20.4 cm shielded!)…L ≈ 60-80 nH

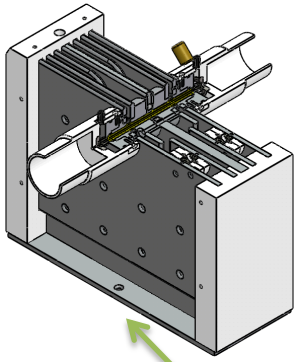
+ Both sides of **capillary opened**.

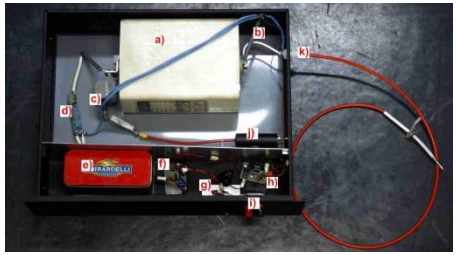
- complex design

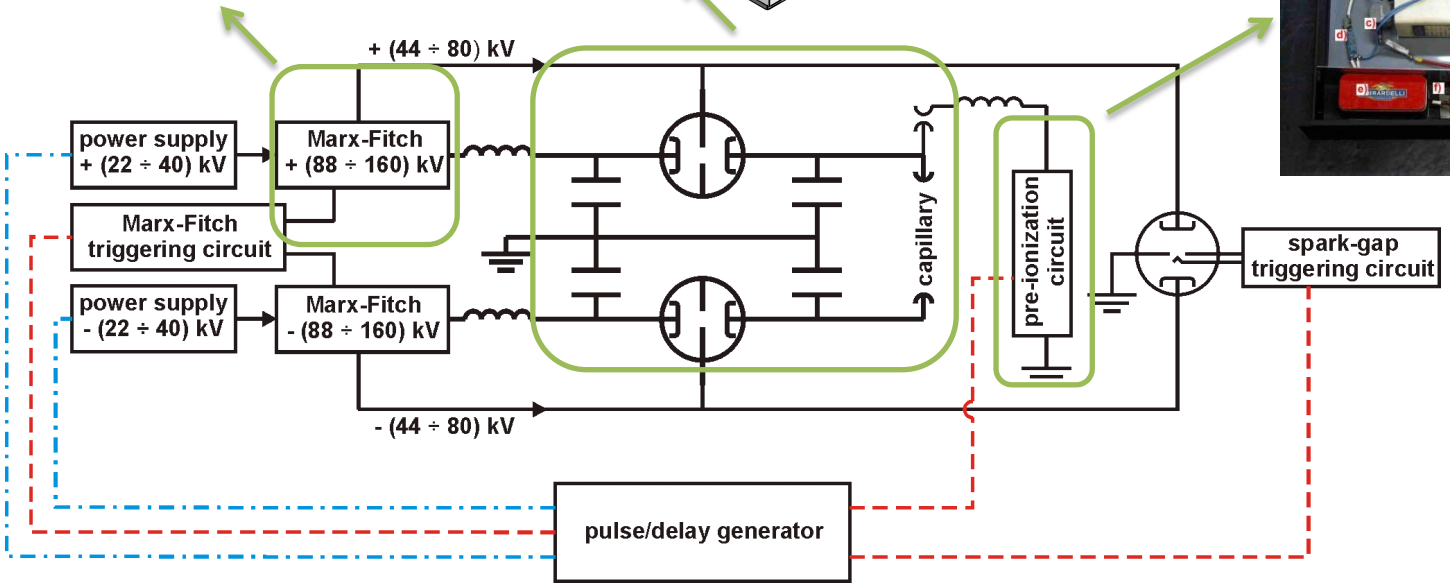
- High voltage at capillary ends.

DRIVER FUNCTIONAL SHEMATIC DRAWING



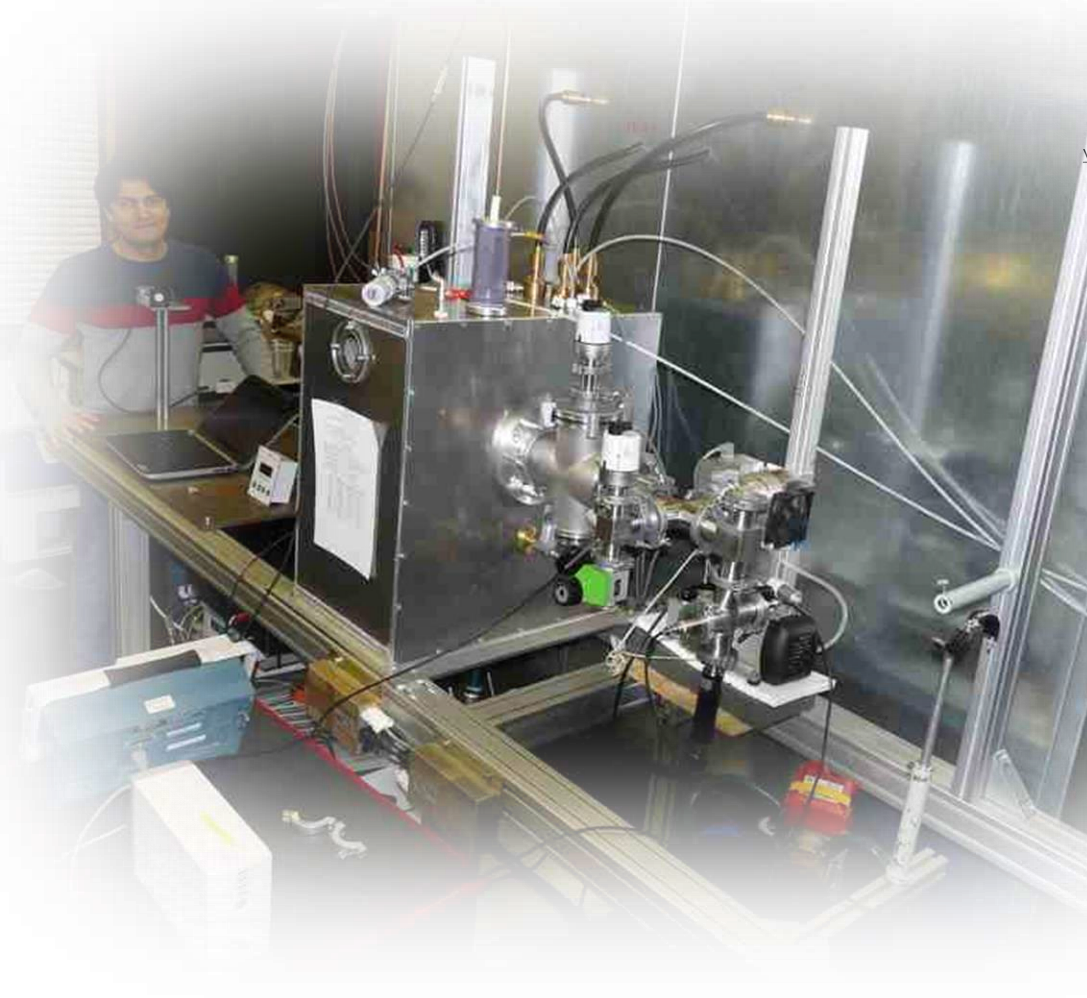


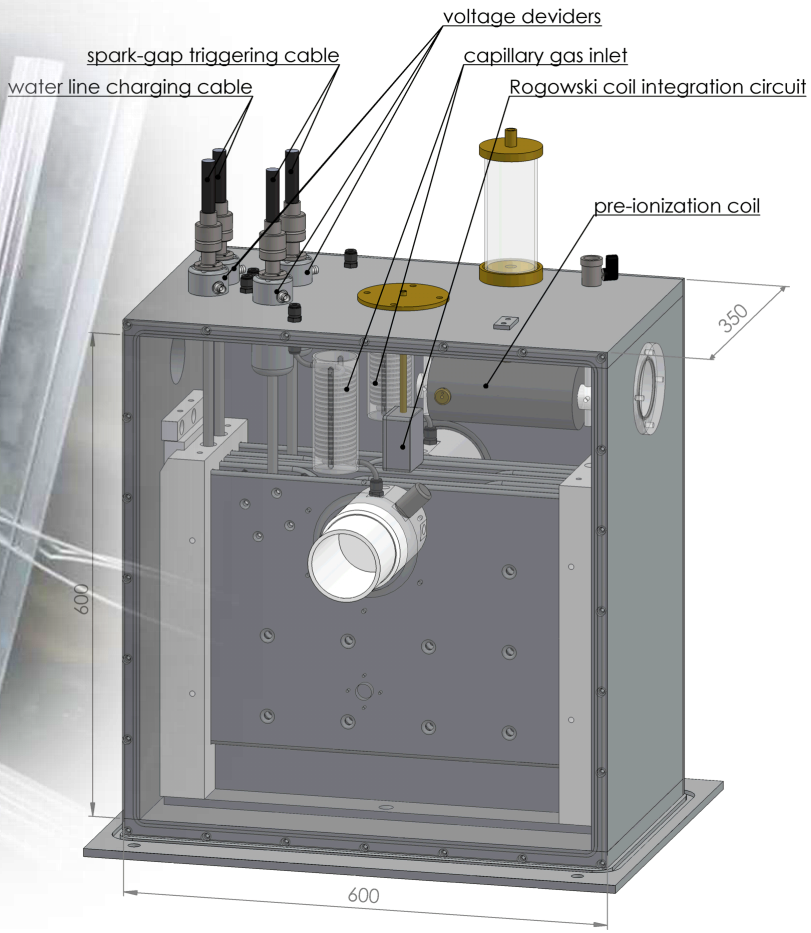




Functional schematic drawing. **Bolt line – discharge circuit**. Blue – electrical driving signal. Red – optical driving signal

ASSEMBLY




voltage deviders
spark-gap triggering cable
capillary gas inlet
water line charging cable
Rogowski coil integration circuit
pre-ionization coil
350
600
600

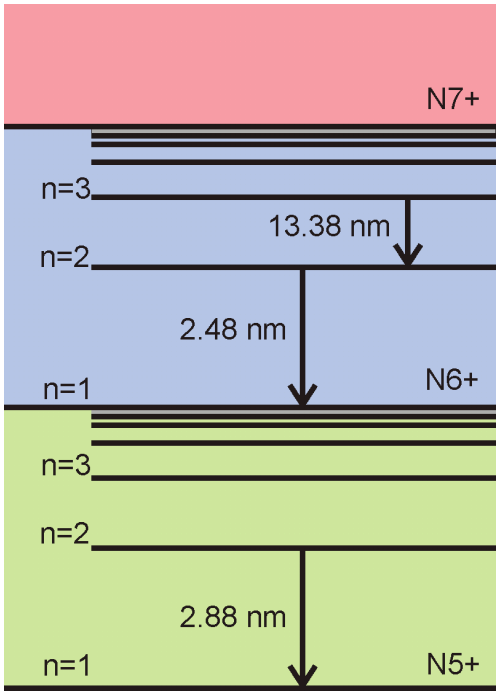
CAN THE DRIVER BE USED AS W-W RADIATION SOURCE?

- At present the driver operates at 55% of expected full-rate current.
- The driver is designed to produce N6+ and N7+ ions at $N_e \sim 10^{19}$ cm^{-3}.
- But we need only N5+ ions.

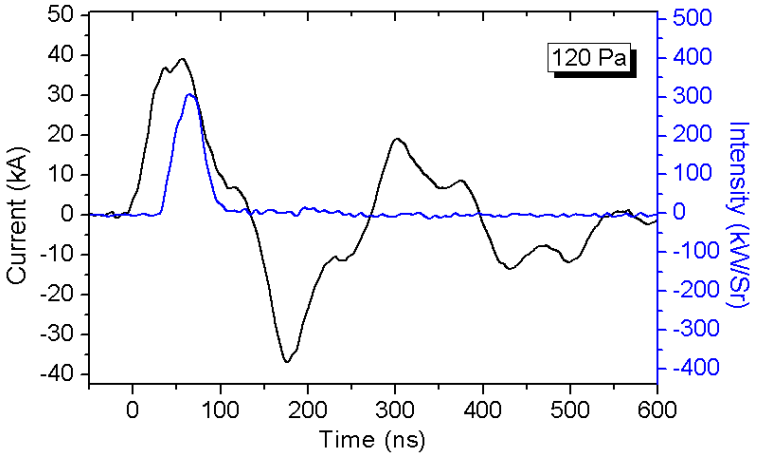
☺ high current ≡ high XUV energy/pulse

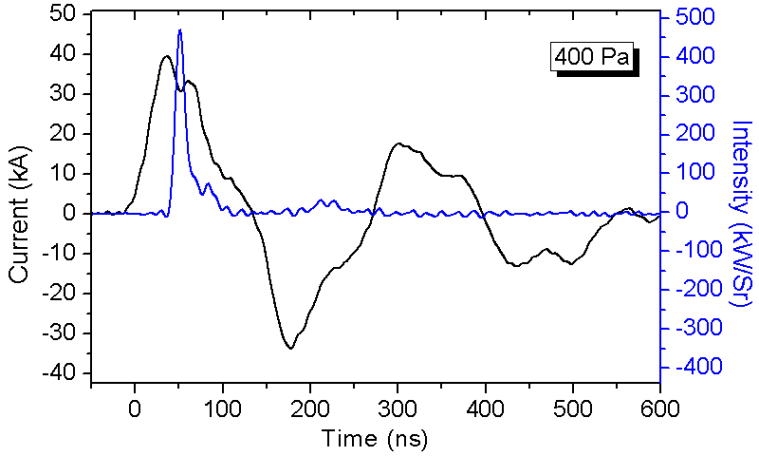
☹ long capillary
low efficiency (self-absorption)
complex design

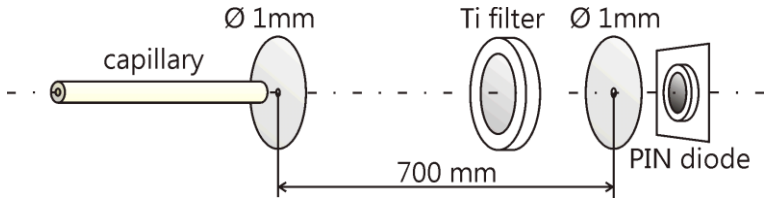
☹ low rep-rate (1 Hz)



DISCHARGE CURRENT AND XUV INTENSITY



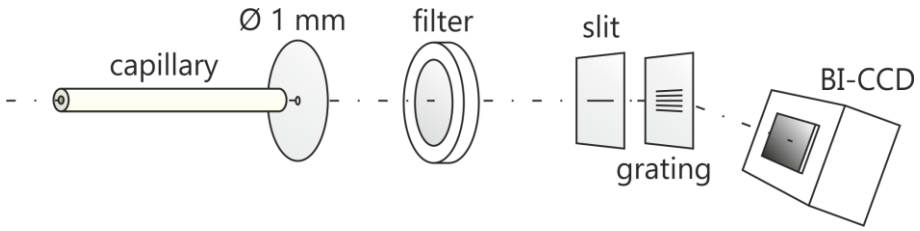




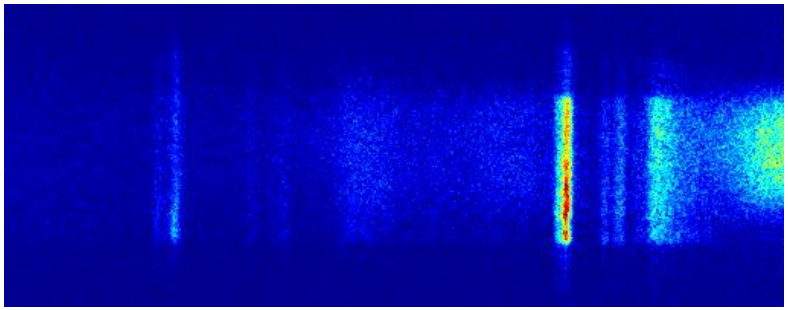
Pressure [Pa]	Peak power (kW/Sr)	Brightness (ph/Sr)	Brightness (ph/Sr)
50	300	9.5	1.4e14
80	250	7.3	1.0e14
120	300	12.0	1.7e14
180	320	10.7	1.5e14
220	390	8.6	1.3e14
400	480	8.4	1.2e14

Values **without** filter

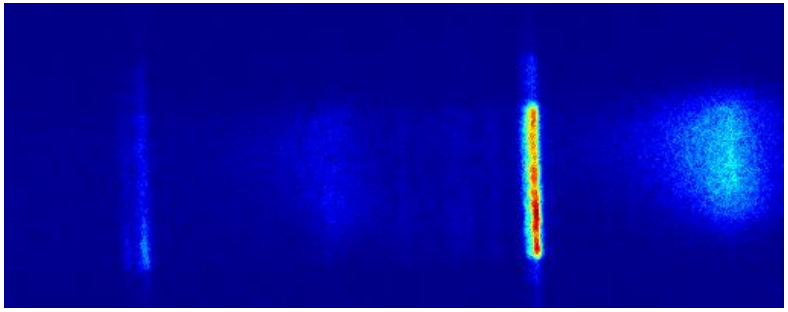
SPECTRA

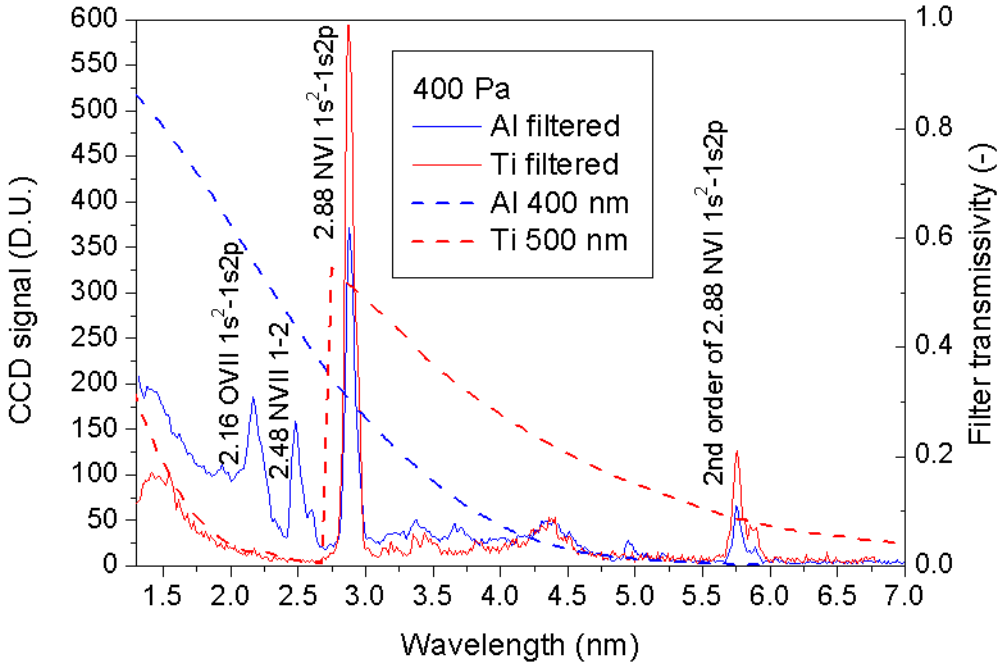


400 nm Ai filter



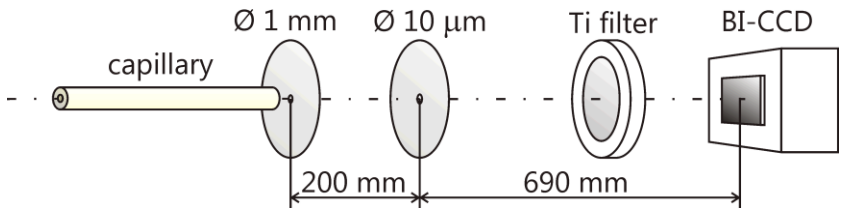
500 nm Ti filter

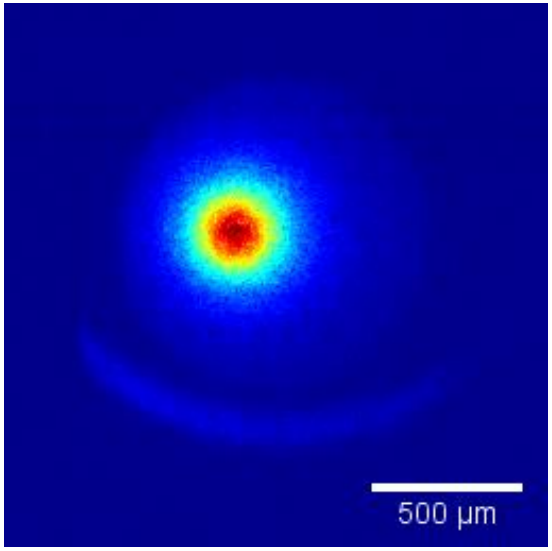


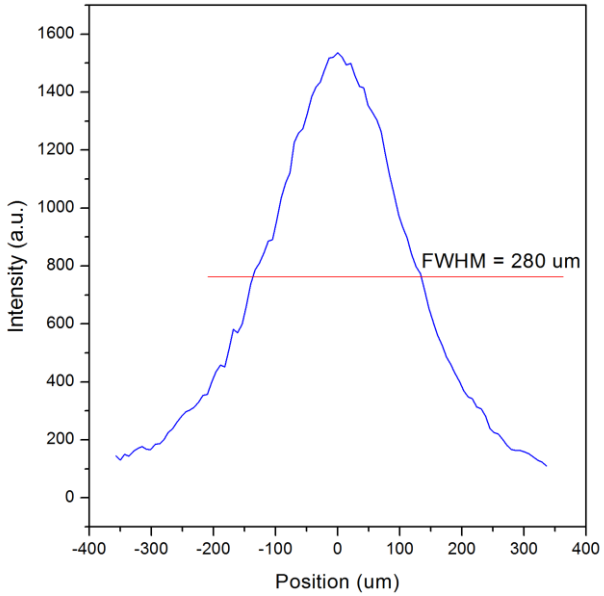


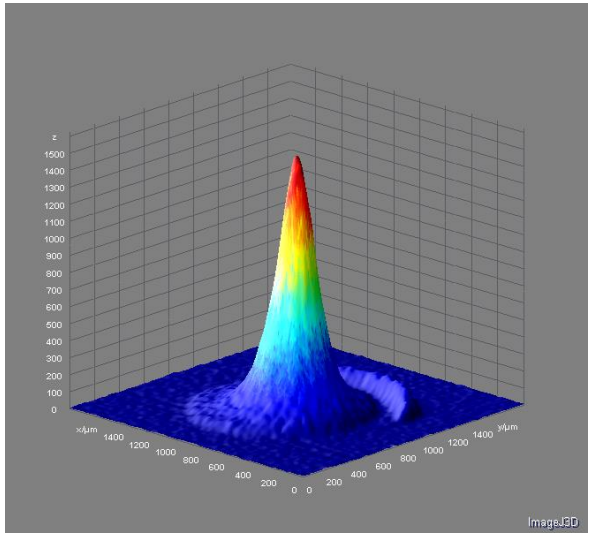
SOURCE IMAGE

- Pinhole image
- FWHM = 280 µm

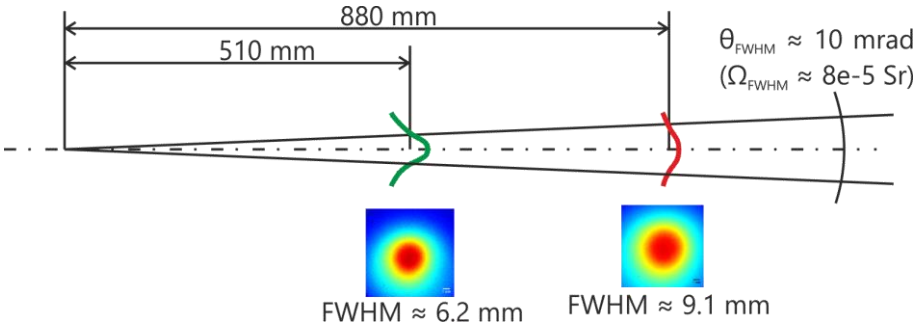


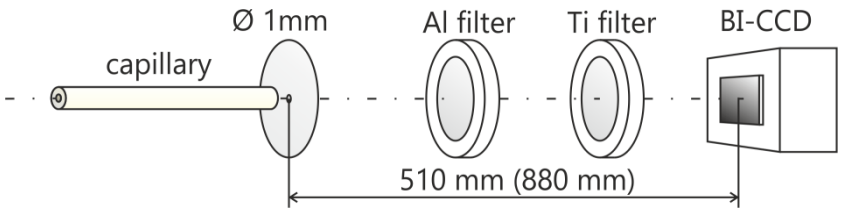




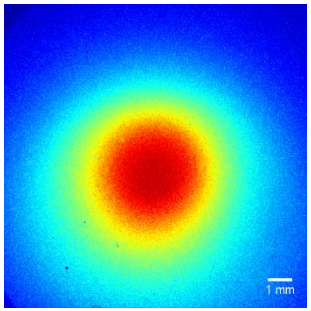


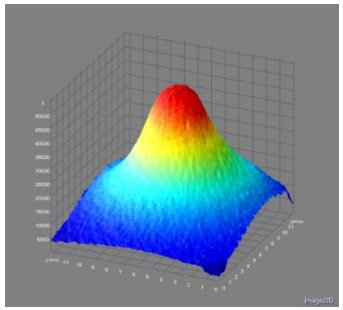
BEAM PROFILE AND DIVERGENCE



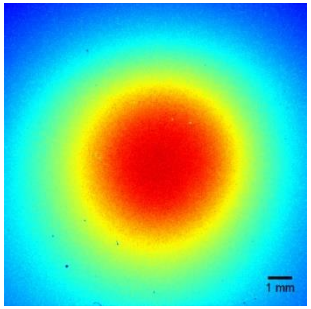


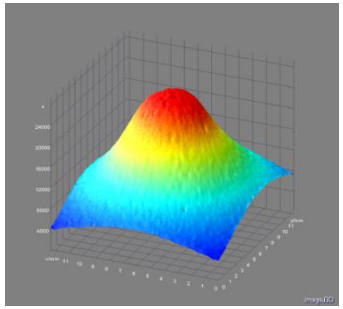
510 mm

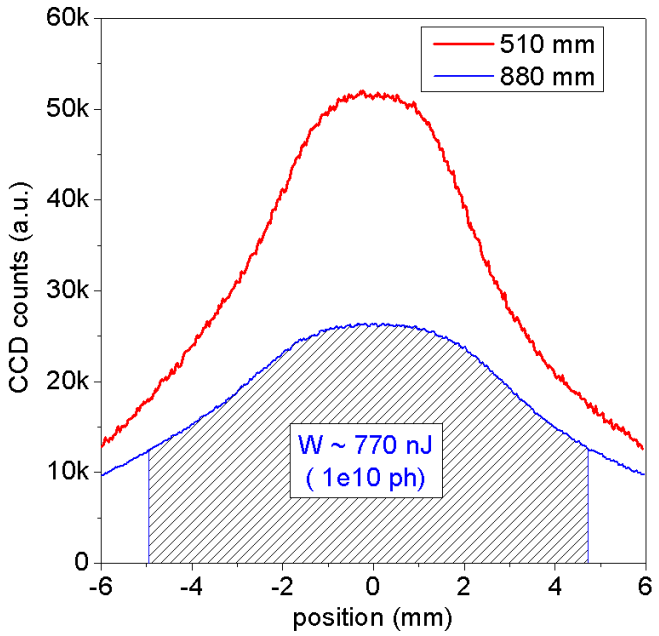




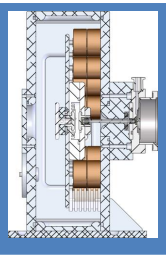
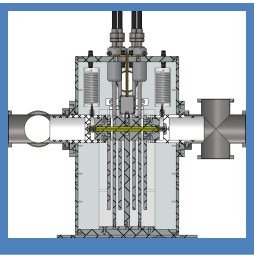
880 mm







SUMMERY

	2009 	2013 
Max. current	27 kA	40 kA*
Rise-time	46 ns	25 ns
Capillary diameter	3.2 mm	3.2 mm
Capillary length	11.3 mm	22.4 mm
source size FWHM	360 µm	270 µm
Beam divergence	30 mrad (7×10^{-4} Sr)	10 mrad (8×10^{-5} Sr)
Peak intensity	87 kW/Sr	480 kW/Sr
Brightness	4 mJ/Sr	12 mJ/Sr
(at 2.88 nm)	5.5×10^{13} ph/Sr	1.7×10^{14} ph/Sr
Energy in the beam	2.24 µJ (3×10^{10} ph)	770 nJ (1×10^{10} ph)

radiance values **without** filter
* 55% of expected full-rate current

CONCLUSOION AND FUTURE PLANS

- Discharge driver for 13.4 nm laser research still in development
- Meanwhile tested as a source at 2.88 nm
  - High peak intensity, low beam divergence
  - Far from optimal design for 2.88 nm (long capillary)

Plans

- Increase discharge current
- Time-resolved discharge plasma diagnostics
- Looking for ASE at 13.4 nm

THANK YOU FOR ATTENTION

ACKNOWLEDGEMENT

This work was supported by the MEYS of the Czech Republic grant no. LG13029.